DHM2020
L. Hanson et al. (Eds.)

doi:10.3233/ATDE200047

The Use and Usage of Virtual Reality Technologies in Planning and Implementing New Workstations

René REINHARD[a,b,1], Peter MÅRDBERG[c], Francisco GARCÍA RIVERA[d], Tobias FORSBERG[e], Anton BERCE[f], Mingji FANG[f] and Dan HÖGBERG[d]
[a]*Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM, 67663 Kaiserslautern, Germany*
[b]*University of Kaiserslautern, Center for Cognitive Science, 67663 Kaiserslautern, Germany*
[c]*Fraunhofer-Chalmers Centre, 412 88 Gothenburg, Sweden*
[d]*University of Skövde, School of Engineering Science, 541 28 Skövde, Sweden*
[e]*Industrial Path Solutions AB, 412 58 Gothenburg, Sweden*
[f]*China-Europe Vehicle Technology CEVT, 417 55 Gothenburg, Sweden*

Abstract. Virtual reality (VR) technologies can support the planning and implementation of new workstations in various industry sectors, including in automotive assembly. Starting in the early planning stages, VR can help in identifying potential problems of new design ideas, e.g. through ergonomics analyses. Designers can then quickly change the virtual representations of new workstations to test solutions for the emerging difficulties. For this purpose, the actions and motions of prospective workers can be captured while they perform the work tasks in VR. The information can also be used as input for digital human modelling (DHM) tools, to instruct biomechanical human models. The DHM tools can then construct families of manikins that differ on anthropometric characteristics, like height, to simulate work processes. This paper addresses both existing technologies for gathering data on human actions and motions during VR usage and ways in which these data can be used to assist in designing new workstations. Here, a novel approach to translate a VR user's actions into instructions for DHM tools through an event-based instruction sampling method is presented. Further, the challenges for utilizing VR are discussed through an industrial use case of the manual assembly of flexible cables in an automotive context.

Keywords. Digital Human Modelling, Virtual Reality, Motion Tracking, Ergonomics, Assembly Path Generation, Automated Manikins, Flexible Cables, Automotive Assembly

1. Introduction

Virtual reality (VR) technologies find increasing application in many industrial settings, including automotive assembly, construction, or energy technologies [1]. This does not only include the assistance of product design through virtual prototypes [2] and VR-

---

[1] Corresponding Author, Email: rene.reinhard@itwm.fraunhofer.de.

based personnel training [3], but also the planning, evaluation, and optimization of assembly processes [4, 5]. For these purposes, VR technologies allow for the interaction with digital prototypes and with virtual representations of planned workstations even during the early planning stages [6]. Industrial case studies indicate the usefulness of VR assisted design of manufacturing workstations compared to design work with only a desktop computer set-up [7]. Thus, in the planning and design of workstations, VR can be used to generate feedback from relevant groups quickly and early in the process, leading to more rapid iterations without the need for costly physical prototypes.

On one hand, experts in subjects like ergonomics can experience and interact with the proposed workstations. Here, the virtual setups can further be used to visualize the results from path planning and digital human modelling (DHM) tools. Thus, the experts can assess the results of assembly simulations and the predicted human motions in an intuitive manner and help evaluate the feasibility, accessibility, and visibility during the installation of digital prototypes, and provide impressions for ergonomic analyses. The gained insights can then be used to adjust the digital work site, to further refine the assembly path and to add to or alter the constraints for the prediction of human motion in DHM tools.

On the other hand, members of the prospective workforce can perform the planned actions in VR while their motions are being tracked [8]. This allows for ergonomics evaluations that take individual characteristics of the workers, their specific restraints and abilities into account. But it also allows for the extraction of data from their tracked movements, which can in turn be used as input for DHM tools.

In this paper, we review currently available VR and tracking technology options and explore their usage in planning new and evaluating existing workstations. In this context, we present a novel event-based instruction sampling approach, in which the actions of VR users are tracked while they are interacting with the digital workstation. This is then used to create a simulation of the manufacturing task, where a digital manikin is instructed based on the actions the VR user performed. This makes it possible to evaluate ergonomics and to repeat the simulation using manikins with different anthropometrics than the original VR user. Moreover, this approach reduces the time needed to setup a DHM simulation and offers a more intuitive approach to construct simulations for non-expert users.

2. Capturing human motions and actions in VR

In order for a VR user to experience a virtual environment and interact with the virtual objects therein, both visualization and tracking technologies are required. In an industrial context, the most commonly utilized VR visualization approaches are projection-based systems and head-mounted displays (HMD) [1, 9]. Projection VR systems include single or multiple projector-based powerwalls, as well as surrounding, walk-in setups, based on multiple projection screens (e.g. Cave Automatic Virtual Environment (CAVE) or CAVE-like systems). However, the current paper focuses on HMD solutions, i.e. display devices which are affixed to the VR user's head and typically include one or two displays as the image source, as well as collimating optics between the eyes and the display.

These systems also typically include on-board inertial measurement units (IMUs) to track rotational movements of the head which are then translated into corresponding orientation changes in the virtual environment [10]. This can further be combined with methods that track the position of the HMD to allow for full 6-DoF movement. This positional tracking usually uses accelerometer dead reckoning as its basis, which is combined with various additional tracking methods to correct the inertial measurement drift [11]. These methods may make use of external hardware, e.g. an external camera that detects infrared signals send from the HMD [12], or lighthouse tracking, where external base stations with stationary LED arrays and active spinning laser emitters send out LED flashes followed by laser sweeps, that are registered by photodiodes on the headset [11, 12]. The positional tracking can also be based on inside-out tracking methods, where cameras on the device estimate the motions of the camera itself relative to the environment they model based on the recorded input [13].

Besides head tracking, modern VR devices often integrate motion tracked handheld controllers, that are tracked and visualized in 3D space and also allow for abstract inputs via button presses [14]. Hereby, they also track the approximate spatial position of the hand holding the controller. Newer VR controller concepts also expand these capabilities with, as of yet, limited finger tracking based on sensors in the controller [15]. This already allows for the usage of some natural motions to interact with virtual objects, like grasping a virtual object by gripping the controller. Some motions, like a pinch grip, can, however, be hindered by the geometry of the controller in the user's hand. Finger tracking can be further extended by other hand and finger tracking technologies, like data gloves or optical tracking, which can translate more natural hand and finger motions into the virtual world. Some data gloves can also expand the feeling of touching virtual objects through tactile feedback, such as actuators on the glove that touch the hand across its surface, or through force feedback, i.e. mechanical forces applied to the finger tips to provide a resistance consistent with touching the object [16].

Lastly, body movements of workers at workstations can be captured. This can be relevant for a range of questions, focusing on topics from posture for ergonomics evaluations, upper body movements for capturing workers performing a task, to gait analyses for logistics analyses on a factory floor. The motion capture can be achieved by a wide variety of approaches: optoelectronic measurements, image processing systems, ultrasonic localization systems, and electromagnetic- or IMU-based systems [17]. Different motion capture systems may be more or less appropriate for certain use cases. As an example, optoelectronic measurements, i.e. active or passive marker-based tracking with usually fixed cameras, offer the most accurate tracking, but can be negatively impacted by obstructions to the line-of-sight or large distances from the cameras [17]. By contrast, IMU systems do not need additional external apparatus, are useful in a mobile context, and are capable of capturing highly dynamic motions, but also need additional information, e.g. from human rigid-body models, to actually offer positional data [17].

In industrial use cases, more elaborate tracking options have been established in the assessment of ergonomics. For example, Daria et al. [18] combined an IMU-based motion capture system connected to Siemens Jack with ErgoLog to perform ergonomics evaluations for workstation simulations. Similarly, Caputo et al. [19] also used an IMU-based motion capture system with Siemens Process Simulate to track posture, which, together with risk screening methods, was used as the basis for ergonomics evaluations.

But the tracked movements of VR users can also be useful for other use cases, e.g. VR-based training. Also, the usage of tracked motions as inputs for DHM tools should be mentioned. For example, Peruzzini et al. [20] used a Vicon optical motion capture system for posture tracking with a Delmia V5-6 for workstation digitalization. Here, they used Catia manikin digitalization and Haption RTI Delmia to connect the VR users' real movements to the virtual manikin's movements. Similarly, Garcia et al. [21] used IPS

VR with IPS IMMA manikins and Smart Textiles to track user movement. These applications in ergonomics evaluations and manikin instruction will be the focus of the following sections.

2.1. VR assisted ergonomics evaluations

The cost of work-related musculoskeletal disorders is considerable both for companies and for the afflicted workers [22]. This includes both direct costs, such as healthcare [23], and indirect losses, e.g. through reduced quality in the production [24]. Such disorders are also psychologically taxing for those who suffer them [25]. The combination of motion capture and VR can help in developing new methods to address these problems.

As the health risks are closely related to the posture of the workers while they perform their jobs, corrective approaches can target posture either via active or passive measures. In active corrections, the operators are informed that their posture is potentially harmful [26], while in passive correction, the workstation's design is improved to facilitate better posture [27]. In order to design workstations that minimize the workers' health risks, standardized ergonomics evaluation methods such as rapid upper limb assessment (RULA), rapid entire body assessment (REBA), or the Ovako working posture analysis system (OWAS) are being utilized [28]. To apply these standards, experts have to either simulate the workers' movements at the workstation using DHM tools, or to run tests by observing real life motions. Traditionally, this design process makes use of 2D screens and physical prototypes. Both approaches have advantages and disadvantages.

DHM tools can be used to economically test design ideas even during early phases of the process and thus spot and address potential problems early on, since they allow for rapid design changes to the workstation, to the performed task and to the anthropometric characteristics of the simulated workers. Yet, the DHMs need to be instructed, which requires expertise, time, and effort to come to representative results. Tests with physical prototypes make direct and easy observations of workers performing the tasks possible, but are also more costly and make changes to the workstation design more complicated. Physical tests will therefore often be used later in the design process.

By including VR in the design process, the designer can conduct studies of ergonomics earlier, without costly physical prototypes, and with the possibility of rapid changes. For this purpose, VR has often been combined with motion capturing technologies [18, 19]. The virtual environment also offers a high degree of control over the situation, including over factors like lighting and noise. However, the use of VR can also have drawbacks. The heavy emphasis on the sense of touch during assembly processes and the expectation of a physical resistance when interacting with virtual structures can often not be adequately simulated. Further, some people may feel less present in the virtual environment, or may even react adversely to VR usage, by developing motion sickness-like symptoms [29]. These individual reactions to VR can in turn impact task performance [29]. Consequently, the face validity of motions tracked in VR may not be as clearly established as it is for real life tests on prototypes. Still, VR can be especially useful for early tests of design ideas and to support the creation of simulations in DHM tools. In order for VR to assist in working with DHM tools, the information about the VR user's actions and motions have to be made usable within the tools. In the following, a new event-based instruction sampling approach is presented, to show how this can be achieved and what requirements it entails.

2.2. VR assisted ergonomics evaluations in DHM tools: An event-based instruction sampling approach

For VR to be of assistance in working with DHM tools, the relevant information from the VR session has to first be recorded and then translated into a form that can be utilized in later simulations. Here, we present a method that approaches this issue through the analysis of a VR user's actions at the virtual workstation, which results in instructions for a DHM tool that uses IPS IMMA [30]. This approach has several requirements, both for the used VR technology and for the DHM tool.

On the side of the adopted VR technology, information about the VR user's movements and interactions in the virtual space have to be captured. This can be realized even with the minimal tracking equipment provided by most current HMD-based VR options, namely the HMD itself and standard handheld VR controllers. While additional tracking information, e.g. from finger or full body tracking, could be gainfully employed, the following will not presuppose access to any additional VR or tracking technology beyond this typical setup, i.e. an HMD that is capable of both rotational and positional tracking and motion tracked VR controllers. On the side of the DHM tool, two functionalities are fundamental to this new method:

- An automated manikin that can interpret and automatically perform instructions with ergonomically sound postures and motions.
- An instruction language that can be mapped against the events in the VR session and that can be interpreted by digital manikins and other objects in the scene.

2.2.1. Automated manikins

A manikin in a DHM system can be said to be automated, if it is able to automatically perform an assembly operation. Thus, if instructed, it will perform a task automatically, without any additional help from the user of the DHM tool. Moreover, the task needs to be performed with ergonomically sound postures and motions which, for instance, need to consider the balance and weight of the manikin's body parts and of any carried objects [31, 32]. The simulation should also consider external forces and torques, while ensuring that the postures and motions are collision free with respect to both the manikin's body parts and the objects in the environment [31, 32].

2.2.2. Instruction language

The instruction language should not be limited to only manikins, since the manikin may interact with other objects in the simulation. All objects used in the simulation can be seen as actors that are performing a set of instructions. Such actors may include geometries, manikins, or mechanical structures, with each actor having its own set of instructions to execute. Thus, simulations with both manikins and other objects in the simulation can be created from the same instruction language [33, 34].

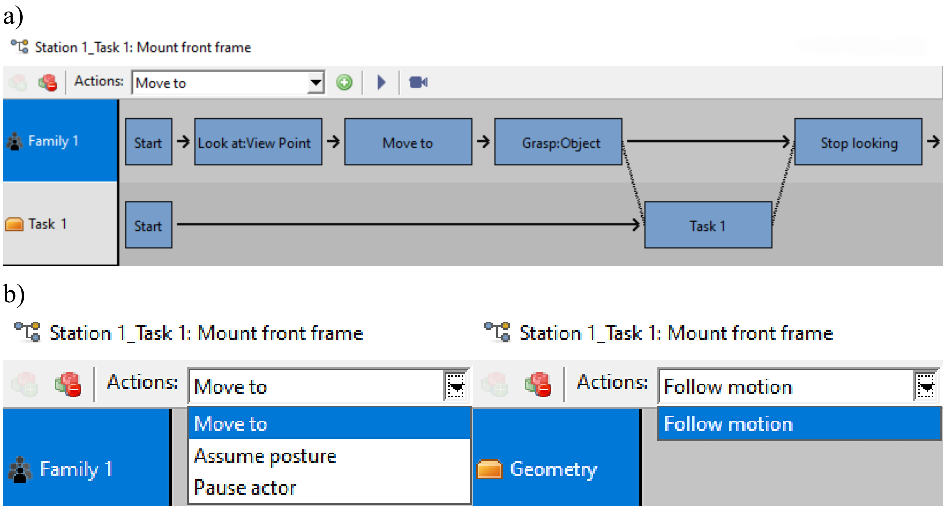

Figure 1. Example of events in the IPS instruction language. a) Interactions between the manikin and an object in the scene with which a task is performed. b) Examples of possible actions for a manikin and object.

The set of instructions that the actors may perform during a simulation should depend on the current state of the actor and on the objects in the simulation. For instance, if the manikin grasps an object with the right hand, then it is not possible for the manikin to grasp another object with the same hand unless the first object has been released [33, 34]. An example of such instructions in the IPS software is illustrated in Figure 1.

Moreover, each instruction must have a corresponding action event in the simulation. For instance, a *grasp* instruction may only be used if there is an object that is available for the manikin to take a hold of. Hence, properties of an object, such as grip, view, and attach points, also define the set of possible instructions for the actors.

Depending on the state of the manikin and on the objects in the environment, work tasks are translated to a sequence of low-level instructions in a controller structure [35]. By following the instruction sequence, a DHM tool like IPS automatically generates collision-free and ergonomically sound manikin motions that accomplish the assembly tasks [35].

2.2.3. Instruction of DHM manikins through event sampling actions in VR

To instruct the manikin, the presented approach uses a sampling procedure that considers all the events that occur while the VR user manipulates virtual objects with the controllers. Each manipulation corresponds to at least one sampled event. Such events may for example include the interaction when the user takes the virtual object, followed by the motion of the object while the VR user holds and moves it to another location. During the VR session, this interaction would correspond to the user pressing a button on the controller to hold the object, to moving it with the motion tracked controllers, and then to releasing the button to let go of the object.

In the presented method, the interaction events in the VR session are translated to the instruction language by mapping them to a fixed set of manikin actions. As an example, when the user is *taking* and *placing* an object, this is translated into corresponding actions of the instruction language, such as *grasp* and *release*. The IMMA manikin uses grip, view, and attach points to interact with objects in the environment. Predefined grip points are automatically created when a VR controller is used to manipulate an object. Currently, a new predefined grip is created where the object is grasped as soon as the VR user takes hold of it.

Moreover, the movements of all objects that the VR user manipulates are also documented in IPS. As an example, during the VR session, the motions of a tracked controller are translated onto a gripped object. The resulting motions are logged and then movement trajectories are created accordingly. These trajectories can then be included in the simulation and correspond to a *follow* instruction in the instructional language. Since all events and trajectories are time stamped, it is possible to construct an instruction sequence for the manikin and all other objects used in the VR session. By following the resulting instruction sequence, a digital simulation of the VR session is created, where the user is represented by the manikin.

2.2.4. Discussion of an event-based instruction sampling approach

In the presented event-based instruction sampling approach, it is possible to capture the actions of VR users to quickly create simulations in a DHM tool, thereby lowering the expertise requirements of using these software options while allowing for their effective usage. In the resulting simulations, it is possible to change the anthropometric characteristics of the manikin and then repeat the simulation for different workers. IPS IMMA contains a built-in functionality to simulate an entire manikin family [36, 37]. Thus, this approach offers a straight forward and cost effective path to ergonomics evaluations of new workstation designs that consider workforce diversity through limited motion capture efforts in VR.

Still, there remain challenges to this approach. When a user picks up an object, a grip point is created. The currently automatically chosen grip type is similar to the way that one grasps the handheld controller, but this might not reflect the VR user's intentions. While grip types can be adjusted later in the DHM tool, this is an additional time demand. One approach to overcome this issue could be to let the user select a grip from a list of predefined grip types which is then automatically aligned, adjusted, and attached to the object. This would reduce the time that is later spend on adjusting the grips in the DHM software, but it also constitutes an action besides naturally interacting with the objects in VR and necessitates a certain degree of expertise to select the correct grip type. Another approach would be to use information from finger tracking technologies to automatically select a fitting grip type. With classical VR controllers, even with the newer models that try to estimate finger positions based on sensors on the controller, this can be a problem. Currently, these controllers can e.g. let VR users naturally grasp a spherical object in the palm of their hand, which corresponds to gripping the controller, but other grip types are not as intuitively translated into VR. In these cases, other finger tracking methods, like data gloves [16], could be useful. However, these options are more costly and come with higher initial time demands for equipping and calibrating the devices. New optical tracking options based on cameras in the HMD could also be useful, but they require a clear line-of-sight to the hand while performing the task, which may not always be possible.

The presented implementation could also be extended by motion tracking for body movements to include complex postural data and actions like squatting or kneeling in the instruction sequence. Future implementations will also focus on capturing interactions with complex objects, including collaborative robots and flexible cables.

Figure 2. An IPS VR user fastening a flexible cable with clips during an assembly task. Courtesy of CEVT.

2.3. Challenges for using VR in planning and implementing workstations exemplified by a use case from the automotive industry

The manual assembly of flexible cables is a common task in the automotive industry today. A corresponding industrial use case from the China Euro Vehicle Technology AB (CEVT) is illustrated in Figure 2. In this use case, the worker should assemble a cable from the floor to the roof of a car along its b-pillar. Here, the cables were fastened into particular places with clips, which are specifically designed for these circumstances. To assemble the cable, it needed to be unfolded, routed, and fastened in a certain order. All of this had to occur while the internal torques and forces of the cable, as well as the forces of the clips needed to be considered. An assembly of this type may also be performed in narrow regions and it may lead to uncomfortable postures for the assembly worker.

As shown in Figure 2, the assembly can be performed by a VR user who guides a manikin to assemble each of the clips along the pillar. The cable can be realistically fastened to the car by stepwise changing the boundary conditions of the cable during the simulation, i.e. by adding constrains to the clips on the cable. This example showcases many of the challenges that VR can encounter when it is applied to complex industrial use cases. To work with the clips, the manikin was instructed to utilize a pinch grip, which did not correspond to the VR users grip on the controller. Further, the assembly occurred at the b-pillar of a car and the VR users would have both expected its resistance when affixing the clips and may have wished to lean on the structure during the assembly. While VR users can be shown a visual impression of their avatar leaning on a virtual object, they themselves are not provided with its physical support. Even current haptic feedback options cannot accurately let the VR users touch and interact with such virtual structures, especially for demanding actions like bodily leaning against them. In addition, the work task required physically correct behavior from the flexible cable in real time at a high frame rate, which, while possible in IPS's VR implementation, can become performance intensive. While some of these challenges can be conquered with new advances in DHM and VR software, as well as with tracking-related hardware, complex bodily interactions with virtual structures can likely only be approached by the introduction of real life elements, like a b-pillar replica in a mixed-reality setup.

3. Conclusion

VR offers many potential benefits for the planning, design, and implementation of new workstations. It can allow for ergonomic assessments even early in the planning phases and, through new methods like the presented event-based instruction sampling approach, VR can also support the work in DHM-related software. The usage of VR does, however, also come with challenges that should be considered. VR can especially be of help in rooting out potential problems early in the design process, while during later stages real life prototype tests and ergonomics assessments may still have clear advantages in some complex use cases.

Acknowledgements

This work has been made possible with support from the Swedish Governmental Agency for Innovation Systems (VINNOVA) within the VIVA and SUMMIT projects, and the Knowledge Foundation within the Synergy Virtual Ergonomics (SVE) project, and the Eurostar project ED-VIMA (E!113330) supported by VINNOVA under the grant number (2019-03534), as well as by the participating organizations. It is also part of the Sustainable Production Initiative and the Production Area of Advance at Chalmers University of Technology. This support is gratefully acknowledged.

References

[1] Berg LP, Vance JM. Industry use of virtual reality in product design and manufacturing: a survey. Virtual Reality, 2017, 21, 1–17.

[2] Wolfartsberger J. Analyzing the potential of Virtual Reality for engineering design review. Automation in Construction, 2019, 104, 27–37.

[3] Gorecky D, Khamis M, Mura K. Introduction and establishment of virtual training in the factory of the future. International Journal of Computer Integrated Manufacturing, 2017, 30, 182–190.

[4] Maropoulos PG, Ceglarek D. Design verification and validation in product lifecycle. CIRP Annals, 2010, 59, 740–759.

[5] Abidi MH, Ahmad A, Darmoul S, Al-Ahmari AM. Haptics Assisted Virtual Assembly. IFAC-PapersOnLine, 2015, 48, 100–105.

[6] Pontonnier C, Dumont G, Samani A, Madeleine P, Badawi M. Designing and evaluating a workstation in real and virtual environment: toward virtual reality based ergonomic design sessions. Journal on Multimodal User Interfaces, 2014, 8, 199–208.

[7] Peruzzini M, Pellicciari M, Gadaleta M. A comparative study on computer-integrated set-ups to design manufacturing systems. Robotics and Computer-Integrated Manufacturing, 2019, 55, 265–278.

[8] Grajewski D, Górski F, Zawadzki P, Hamrol A. Application of Virtual Reality techniques in design of ergonomic manufacturing workplaces. Procedia Computer Science, 2013, 25, 289–301.

[9] Liagkou V, Salmas D, Stylios C. Realizing Virtual Reality learning environment for Industry 4.0. Procedia CIRP, 2019, 79, 712–717.

[10] Desai PR, Desai PN, Ajmera KD, Mehta K. A review paper on Oculus Rift: A Virtual Reality headset. International Journal of Engineering Trends and Technology, 2014, 13, 175–179.

[11] Niehorster DC, Li L, Lappe M. The Accuracy and precision of position and orientation tracking in the HTC Vive Virtual Reality system for scientific research. Iperception, 2017, 8, 2041669517708205.

[12] Borrego A, Latorre J, Alcañiz M, Llorens R. Comparison of Oculus Rift and HTC Vive: Feasibility for Virtual Reality-based exploration, navigation, exergaming, and rehabilitation. Games for Health Journal, 2018, 7, 151–156.

[13] Gourlay MJ, Held RT. Head-Mounted-Display tracking for Augmented and Virtual Reality. Information Display, 2017, 33, 6–10.

[14] Reski N, Alissandrakis A. Open data exploration in Virtual Reality: A comparative study of input technology. Virtual Reality, 2020, 24, 1–22.

[15] Arimatsu K, Mori H. Evaluation of machine learning techniques for hand pose estimation on handheld device with proximity sensor. In: CHI Conference on Human Factors in Computing Systems, 2020, New York, USA, 1–13.

[16] Perret J, Poorten EV. Touching Virtual Reality: A review of haptic gloves. In: Borgmann H, editor. ACTUATOR 2018: 16th International Conference on New Actuators, 2018, Bremen, Germany, 1–5.

[17] van der Kruk E, Reijne MM. Accuracy of human motion capture systems for sport applications: State-of-the-art review. European Journal of Sport Science, 2018, 18, 806–819.

[18] Daria B, Martina C, Alessandro P, Fabio S, Valentina V, Zennaro I. Integrating mocap system and immersive reality for efficient human-centred workstation design. IFAC-PapersOnLine, 2018, 51,188-193.

[19] Caputo F, Greco A, d'Amato E, Notaro I, Spada S. A preventive ergonomic approach based on virtual and immersive reality. In: Rebelo F, Soares M, editors. Advances in Ergonomics in Design, Springer International Publishing, Cham, Switzerland, 2018, 3–15.

[20] Peruzzini M, Carassai S, Pellicciari M. The benefits of human-centred design in industrial practices: Re-design of workstations in pipe industry. Procedia Manufacturing, 2017, 11, 1247–1254.

[21] García Rivera F, Brolin E, Syberfeldt A, Högberg D, Iriondo Pascual A, Perez Luque E. Using Virtual Reality and smart textiles to assess the design of workstations. In: Proceedings of the 9th Swedish Production Symposium (SPS2020), 2020, Oct 6-9, Jönköping, Sweden.

[22] Bhattacharya A. Costs of occupational musculoskeletal disorders (MSDs) in the United States. International Journal of Industrial Ergonomics, 2014, 44, 448–454.

[23] Ramos DG, Arezes PM, Afonso P. Analysis of the return on preventive measures in musculoskeletal disorders through the benefit-cost ratio: A case study in a hospital. International Journal of Industrial Ergonomics, 2017, 60, 14–25.

[24] Falck A-C, Rosenqvist M. A model for calculation of the costs of poor assembly ergonomics (part 1). International Journal of Industrial Ergonomics, 2014, 44, 140–147.

[25] Jose JA. Outcome measures and prognosis of WRMSD. Work, 2012, 41 Suppl 1, 4848–4849.

[26] Mahdavian N, Lind CM, Diaz-Olivares J, Pascual A, Högberg D, Brolin E, et al. Effect of giving feedback on postural working techniques. In: Advances in transdisciplinary engineering, 2018, 247-252.

[27] Shikdar AA, Al-Hadhrami MA. Smart workstation design: An ergonomics and methods engineering approach. International Journal of Industrial and Systems Engineering, 2005, 2, 363–374.

[28] David GC. Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. Occupational Medicine, 2005, 55, 190–199.

[29] Weech S, Kenny S, Barnett-Cowan M. Presence and cybersickness in Virtual Reality are negatively related: A review. Frontiers in Psychology, 2019, 10, 158.

[30] Högberg D, Hanson L, Bohlin R, Carlson JS. Creating and shaping the DHM tool IMMA for ergonomic product and production design. International Journal of the Digital Human, 2016, 1, 132–152.

[31] Bohlin R, Delfs N, Hanson L, Högberg D, Carlson JS. Automatic creation of virtual manikin motions maximizing comfort in manual assembly processes. In: Hu SJ, editor. 4th CIRP Conference on Assembly Technologies and Systems, 2012, Ann Arbor, USA, 209–212.

[32] Delfs N, Bohlin R, Hanson L, Högberg D, Carlson J. Introducing stability of forces to the automatic creation of digital human postures. In: 2nd International Digital Human Modeling Symposium (DHM2013), 2013.

[33] Mårdberg P, Carlson JS, Bohlin R, Delfs N, Gustavsson S, Keyvani A, Hanson L. Introducing a formal high-level language for instructing automated manikins. In: 2nd International Digital Human Modeling Symposium (DHM2013), 2013.

[34] Mårdberg P, Carlson JS, Bohlin R, Delfs N, Gustafsson S, Hanson L. Using a formal high-level language to instruct manikins to assemble cables. Procedia CIRP, 2014, 23, 29–34.

[35] Mårdberg P, Yan Y, Bohlin R, Delfs N, Gustafsson S, Carlson JS. Controller hierarchies for efficient virtual ergonomic assessments of manual assembly sequences. Procedia CIRP, 2016, 44, 435–440.

[36] Hanson L, Högberg D, Carlson JS, Delfs N, Brolin E, Mårdberg P, et al. Chapter 11 - Industrial Path Solutions – Intelligently Moving Manikins. In: Scataglini S, Paul G, editors. DHM and posturography: Academic Press, Cambridge, 2019, 115–124.

[37] Brolin E. Anthropometric diversity and consideration of human capabilities: Methods for virtual product and production development [PhD Thesis]. Göteborg: Chalmers University of Technology, 2016.